Flood risk analyses – how detailed do we need to be?

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Abstract

Applied flood risk analyses, especially in urban areas, very often pose the question how detailed the analysis needs to be in order to give a realistic figure of the expected risk. The methods used in research and practical applications range from very basic approaches with numerous simplifying assumptions up to very sophisticated, data and calculation time demanding applications both on the hazard and vulnerability part of the risk. In order to shed some light on the question of required model complexity in flood risk analyses and outputs sufficiently fulfilling the task at hand, a number of combinations of models of different complexity both on the hazard and vulnerability side were tested in a case study. The different models can be organized in a model matrix of different complexity levels: On the hazard side the approaches/models selected were A) linear interpolation of gauge water levels and intersection with a digital elevation model (DEM), B) a mixed 1D/2D hydraulic model with simplifying assumptions (LISFLOOD-FP) and C) a Saint-Venant 2D zero-inertia hyperbolic hydraulic model considering the built environment and infrastructure. On the vulnerability side the models used for the estimation of direct damage to residential buildings are in order of increasing complexity: I) meso-scale stage-damage functions applied to CORINE land cover data, II) the rule-based meso-scale model FLEMOps+ using census data on the municipal building stock and CORINE land cover data and III) a rule-based micro-scale model applied to a detailed building inventory. Besides the inundation depths, the latter two models consider different building types and qualities as well as the level of private precaution and contamination of the floodwater. The models were applied in a municipality in southeast Germany, Eilenburg. It suffered extraordinary damage during the flood of August 2002, which was well documented as were the inundation extent and depths. These data provide an almost unique data set for the validation of flood risk analyses. The analysis shows that the combination of the

1D/2D-model and the meso-scale damage model FLEMOps+ performed best and provide the best compromise between data requirements, simulation effort, and an acceptable accuracy of the results. The more detailed approaches suffered from complex model setup, high data requirements, and long computation times.

Keywords: flood risk, hydraulic modelling, damage estimation, prediction uncertainty, model performance

1 Introduction

1.1 Risk analyses

Risk-oriented methods and risk analyses are gaining more and more attention in the fields of flood design and flood risk management since they allow us to evaluate the cost-effectiveness of mitigation measures and thus to optimise investments (e.g. Resendiz-Carrillo and Lave 1990; USACE 1996; Olsen et al. 1998; Al-Futaisi and Stedinger 1999; Ganoulis 2003; Hardmeyer and Spencer 2007). Moreover, risk analyses quantify the risks and thus enable (re-)insurance companies, municipalities and residents to prepare for disasters (e.g. Takeuchi 2001; Merz and Thieken 2004).

The Flood Directive of the European Commission (EU 2007) requires flood risk maps for all river basins and sub-basins with significant potential risk of flooding in Europe. The most common approach to define flood risk is the definition of risk as the product of hazard, i.e. the physical and statistical aspects of the actual flooding (e.g. return period of the flood, extent and depth of inundation), and the vulnerability, i.e. the exposure of people and assets to floods and the susceptibility of the elements at risk to suffer from flood damage (e.g. Mileti 1999; Merz and Thieken 2004). This definition is adopted in the Flood Directive (EU 2007). Following this definition, meteorological, hydrological and hydraulic investigations to define the hazard and the estimation of flood impact to define vulnerability can be undertaken separately in the first place, but have to be combined for the final risk analysis.

Clearly, risk quantification depends on spatial specifications (e.g., area of interest, spatial resolution of data) and relies on an appropriate scale of the flood hazard and land-use maps. For instance, for planning and cost-benefit analysis of flood-

mitigation measures and for the preparedness and mitigation strategies of different stakeholders (communities, companies, house owners etc.), very detailed spatial information on flood risk is necessary. For both the hazard and vulnerability analysis a number of approaches and models of different complexity are available and many of them were used in scientific as well as applied flood risk analyses and on different scales. Examples of flood risk analyses are available on municipal level (Baddiley 2003; Grünthal et al. 2006), catchment level (MURL 2000; ICPR 2001; Dutta et al. 2003; Dutta et al. 2006), on a national scale (Hall et al. 2003; Rodda 2005) and European level (Schmidt-Thomé et al. 2006).

1.1.1 Hazard analyses

Hazard analyses give an estimation of the extent and intensity of flood scenarios and associate an exceedance probability to it (Merz and Thieken 2004). The usual procedure is to apply a flood frequency analysis to a given record of discharge data (e.g. Stedinger et al. 1993) and to transform the discharge associated to defined return periods, e.g. the 100 year event into inundation extent and depths. This apparently simple approach has a number of pitfalls and uncertainties, which need to be considered. These uncertainties stem e.g. from the inappropriateness of the extreme value function for the given data series, violation of the underlying assumptions of the extreme value statistics, i.e. stationarity and homogeneity of the data series, and shortness of the data series and large uncertainties in the extrapolation range (e.g. Apel et al. 2008). But also the hydraulic transformation has a number of methodological problems, which are usually associated with the selection of the appropriate model, the consideration of dikes and even more dike breaches and the calibration and validation of the models. Depending on the scale of the hazard or risk analysis the complexity of models applied range from simple interpolation methods to sophisticated and spatially detailed models solving the shallow water equations in two dimensions. However, the correctness of the models can usually be qualitatively evaluated only, because sufficient data on inundation extent and depths for the calibration and validation of the models is lacking. Therefore the question of how detailed a model should be in order to give reasonable results is often answered pragmatically given the available resources and data and is not based on quantitative goodness of fit estimates. In the presented study this problem is explicitly addressed because an extensive data set

on inundation extent and depths could be collected during and after the large flood of the Elbe and its tributaries in August 2002 in Germany.

1.1.2 Vulnerability analyses

Vulnerability analyses are normally restricted to the estimation of detrimental effects caused by the floodwater like fatalities, business interruption or financial/economic losses. Frequently, vulnerability analyses focus only on direct flood loss which is estimated by damage or loss functions. Most flood loss models have in common that the direct monetary flood loss is a function of the type or use of the building and the inundation depth (Smith 1981; Krzysztofowicz and Davis 1983; Wind et al. 1999; NRC 2000; Green 2003). Such depth-damage functions are seen as the essential building blocks upon which flood loss analyses are based and they are internationally accepted as the standard approach to assessing urban flood loss (Smith 1994). Usually, building-specific damage functions are developed by collecting flood loss data in the aftermath of a flood. Another data source are "what-if analyses" (ex-ante analysis), by which the damage which is expected in case of a certain flood situation is estimated, e.g. "Which damage would you expect if the water depth was 2m above the building floor?". On the base of such actual and synthetic data generalized relationships between damage and flood characteristics have been derived for different regions (e.g. Green, 2003; Penning-Rowsell et al. 2005; Scawthorn et al. 2006).

Recent studies have shown that estimations based on stage-damage functions may have a large uncertainty since water depth and building use only explain a part of the data variance (Merz et al. 2004). It is obvious that flood loss depends, in addition to building type and water depth, on many factors, e.g. on flow velocity, duration of inundation, availability and information content of flood warning, precaution and the quality of external response in a flood situation (Smith 1994; Wind et al. 1999; Penning-Rowsell and Green 2000; ICPR 2002; Kelman and Spence 2004; Kreibich et al. 2005). Some flood loss models include parameters like flood duration, contamination, early warning or precautionary measures (Penning-Rowsell et al. 2005; Büchele et al. 2006; Thieken et al. 2006). While the outcome of most of the functions is the absolute monetary loss of a building, some approaches provide relative loss functions, i.e. the loss is given in percentage of the building or content value (e.g. Dutta et al. 2003; Thieken et al. 2006), or as

index values, e.g. loss may be expressed as an equivalent to the number of median-sized family houses totally destroyed (Blong 2003). If these functions are used to estimate the loss due to a given flood scenario property values have to be predetermined.

As outlined by Messner and Meyer (2005) flood loss estimation can be performed on different scales: In small investigation areas with detailed information about type and use of single buildings micro-scale analyses can be undertaken. Here, flood loss is evaluated on an object level, e.g. at single buildings. For bigger areas a meso-scale approach is advantageous. These approaches are based on aggregated land cover categories, which are connected to particular economic sectors. Loss is then estimated by aggregated sectoral models (Messner and Meyer 2005).

1.2 Validation and data requirements

Despite the large number of flood risk analyses there is still no study present that investigates the performance of different approaches and models compared to an actual flood event. The reason for this is the scarcity of valuable calibration and validation data, for both, hazard and vulnerability models. For a thorough calibration and validation of any flood risk analysis numerous data sets are necessary. For the hazard side, which is usually covered by a hydraulic model, this would ideally be

- up- and downstream flow hydrographs
- mapped inundation extents
- recorded inundation depths, especially in urban areas
- flow velocities in case of rivers with high flow velocities

For the vulnerability side the data demands depend on the type of flood loss considered and the chosen modelling approach. In this paper, flood loss estimation is restricted to direct monetary damage at residential buildings. Different model approaches at the meso- as well as at the micro-scale are applied. Basically the following data sets are required:

- hazard data of the event: inundation extent and depths,
- exposure data: building inventory, especially the location of buildings, or land cover data; types and asset values of buildings,

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- susceptibility data: building characteristics, and further data sets depending on the flood loss model,
- flood loss data: total amount of damage due to the flood event under study, e.g. the sum of all residential building repair costs.

Comprehensive calibration and validation data sets like these are hardly available. Damage data are rarely gathered, (initial) repair cost estimates are uncertain and data are not updated systematically (Dowton and Pielke 2005). Let alone the problem of obtaining quality elevation and river morphology data. Hence the question of performance of different flood risk analysis approaches could not be investigated until now. However, during and after the extreme flood in the catchments of the rivers Elbe and Danube in August 2002 that caused a total flood loss of 11600 million Euro in Germany, quite a large number of data could be collected. Therefore, the list above could be almost completed in some parts of the affected area.

1.3 Objectives

In this paper, a comparative risk analysis study is presented with three different types of hydraulic and flood loss models taking the municipality Eilenburg at the river Mulde in Saxony, Germany, as an example. Based on the performance of different model combinations, which were evaluated with the collected flood and flood loss data, a recommendation of a combination of hazard and flood loss model is given, representing the best compromise between accuracy and modelling effort. The paper is structured as follows: In chapter 2, the three hazard models and the three types of vulnerability models are presented. The case study area, the city of Eilenburg in Germany is described in chapter 3. Results are given in chapter 4, explaining the hydraulic model set up (4.1) and showing the results of the hazard analysis (4.2) and flood loss estimation (4.3). Chapter 5 contains the discussion and conclusions.

2 Model descriptions

For the comparative study we selected models of three different complexity levels for both the hazard and flood loss analysis. Each hazard model was combined with each flood loss model. This resulted in a model combination matrix shown in

Figure 1. The flood loss estimates of all combinations were finally compared to official flood loss data in order to evaluate the overall model performance. Since the official flood loss data consisted of 765 single records a resampling algorithm (bootstrap, Efron 1979) could be applied to derive a frequency distribution of the total flood loss sum. Loss estimates that fall within the 95% interval of the resampled loss data were assumed to be acceptable. Other combinations which led to results outside the 95% confidence interval were assumed as insufficiently accurate and were rejected.

The hazard models selected were in order of ascending complexity: A) linear interpolation of gauge levels and intersection with a DEM, B) a coupled 1D/2D hydraulic model and C) a Saint-Venant 2D zero-inertia hyperbolic hydraulic model. For comparison we also included a data driven approach to derive the water depths by intersecting a water mask of an observed flood event with the DEM. While this approach doesn't allow any extrapolation to other events, it can be taken as a benchmark for the evaluation of quality of the model results.

For the flood loss estimation I) meso-scale stage-damage functions, II) a rule-based meso-scale model and III) a rule-based micro-scale damage model were chosen. The flood loss assessment was restricted to direct losses at residential buildings. All models are relative models, estimating first the flood loss ratio, i.e. the economic loss of the building divided by the total value of the building. These results are then multiplied with the affected assets, i.e. the values of the buildings to gain the estimated total economic loss of the residential buildings.

The following paragraphs give a brief description of the models:

Figure 1

2.1 Hazard model A: Linear Interpolation

Linear interpolation is the simplest way to reconstruct floodplain inundation from measured gauge levels: Water levels at gauging stations, either measured during an event or synthetically derived, are linearly interpolated for any point of the reach between the gauges and hence a uniform sloping flood level is created. This level is intersected with a DEM. All areas below the interpolated flood levels are indicated as inundated and the inundation water depth is the difference between

the terrain elevation and the flood level. For this study, modelling results from the work of Grabbert (2006) were used.

The method is very simple and thus suffers from a number of drawbacks. For example, there is no volume control of the floodplain inundation, which results in huge and unrealistic flooded areas especially in unbounded lowlands. Moreover, the effects of dike lines are often neglected, because they are normally not or hardly represented in the DEM. Further, the actual dynamics of the inundation process are completely neglected.

A similar cut and fill procedure was performed for the benchmark scenario. Here, the water mask of the maximum inundation extend of a flood event derived from satellite data was intersected with the DEM. By this approach the disadvantages of the linear interpolation are avoided and the derived inundation depths can be regarded as the best spatially distributed representation of the maximum inundation depths of the observed flood event.

2.2 Hazard model B: 1D/2D-model

In this approach the hydrodynamics are represented one-dimensionally in the actual stream, whereas the floodplain inundation is modelled spatially explicit in a two-dimensional fashion. In this study, the model LISFLOOD-FP (Bates and De Roo, 2000) was used. In this model the river channel is simplified by a rectangular channel and for the hydrodynamics the kinematic wave model is used. The 2D-part is a storage cell model based on the DEM with spatial explicit flows in x- and y-directions, which are calculated with an approach identical to the diffusion wave simplification of the full St.-Venant equations (Chow et al., 1988). This model needs a basic data set regarding the channel presentation (a number of cross section definitions consisting of coordinates, bed elevation, channel width and roughness coefficient), a DEM and spatial explicit roughness coefficients for the floodplain inundation. These data sets are comparatively easy to obtain and an initial model setup can be done within a short time with the help of a DEM, land cover maps that are used for the roughness coefficient estimation and topographical maps for basic channel data. However, while being sufficiently exact in natural flow conditions on floodplains, the model is not able to represent the flow conditions in a built environment correctly, because the obstructions caused by the buildings are not explicitly taken into account.

2.3 Hazard model C: 2D-model

In order to model the flow regime in an urban area a more detailed, full two-dimensional model has to be used, which is able to consider the hydraulically important features like streets, buildings, channels etc. In this study we applied the model of (Aronica et al., 1998). This model is based on the St.-Venant equations for two-dimensional shallow-water flow, with convective inertial terms neglected in order to eliminate the related numerical instabilities. The St.-Venant equations are solved using a finite element technique with triangular elements. The finite element approach proposed allows to avoid a simplified description of the hydraulic behaviour of flooded areas due to the fact that triangular elements are capable of reproducing the detailed complex topography of the built-up areas, i.e. blocks, street networks, etc. exactly as they appear within the floodable area with an appropriately constructed mesh (Aronica and Lanza 2005). Blocks and other obstacles are treated as internal islands within the triangular mesh covering the entire flow domains.

This model needs a basic data set regarding the floodplain topography (topographical map with a scale of 1:10000 and lower), a high spatial resolution DEM (in comparison with the spatial resolution of the finite element discretisation) and spatially explicit roughness coefficients for the floodplain inundation. In addition, a data set about the river topography, i.e. a number of cross section definitions with bed elevations, channel widths and roughness coefficients are necessary to improve the mesh descriptive capability in those parts of floodplains (Horritt and Bates 2001).

2.4 Vulnerability model type I: meso-scale stage-damage functions

In this study, three different types of stage-damage functions are used, which have been applied in flood action plans or risk zonation projects in Germany. Unfortunately, the studies give no detailed information about the data and methods used to derive the stage-damage functions. However, all are using flood loss data from the German flood loss data base HOWAS (Buck and Merkel, 1999) and expert judgement. All models are suitable for applications on the meso-scale, i.e. for the application to land cover units.

In the MURL-Model (MURL 2000), the damage ratio to buildings is given by a linear function $D = 0.02h$ where D is the damage ratio and h the water level given in meter. For water levels of more than 5 m the damage ratio is set to 10 %. In the ICPR-Model (ICPR 2001), damage at residential buildings is estimated by the relation $D = (2h^2 + 2h)/100$, where D is the damage ratio and h is the water level given in meter.

For some flood action plans, a third function was used: $D = (27 \sqrt{h})/100$, where D is the damage ratio and h is the water level given in meter (HYDROTEC 2001). First, these functions are applied to an inundation scenario in order to estimate the damage ratio per grid cell. These ratios are then each multiplied by the specific asset value assigned to the corresponding grid cell. The total asset value of residential buildings was taken from the work of Kleist et al. (2006). Since only the total asset sum is provided for each municipality, the assets are disaggregated on the basis of the CORINE land cover data 2000 (further referred to as CLC2000) and a dasymetric mapping approach based on Mennis (2003).

2.5 Vulnerability model type II: the meso-scale *Flood Loss Estimation MOdel for the private sector* (FLEMOps)

To account for more damage-influencing factors, the rule-based Flood Loss Estimation MOdel for the private sector FLEMOps has been developed. The model is based on detailed statistical analysis (e.g. Mann-Whitney-U tests, principal component analyses) of data from a survey of 1697 private households that were affected by the flood in August 2002 (Kreibich et al. 2005; Thieken et al. 2005). The model calculates the damage ratio at buildings for five classes of inundation depths, three distinct building types and two categories of building quality. In an additional modelling step (further FLEMOps+), also the influence of the contamination of the floodwater and precaution of private households can be considered by scaling factors (see Büchele et al. 2006). The model can be applied to the micro-scale, i.e. to single buildings (vulnerability model type III) as well as to the meso-scale, i.e. to land cover units. For the latter, a scaling procedure based on census data and a dasymetric mapping technique was developed (Thieken et al. 2006): By means of INFAS Geodaten (2001) and cluster analysis the mean building composition and the mean building quality per

municipality was derived for whole Germany. With the help of this classification, a mean flood loss model was set up by weighting the flood loss model for three different building types by the mean percentages of these building types in each cluster. For example: The mean composition of residential buildings in the municipality of Eilenburg is represented by cluster 2, i.e. 31 % of the houses are one-family homes, 25 % are (semi-)detached houses and 44 % are multifamily houses. According to the INFAS data, the mean building quality in Eilenburg is slightly below average. Thus, the mean damage ratios DR_{mean} for Eilenburg are calculated with:

$$DR_{mean} = 0.31 * DR_{OFH} + 0.25 * DR_{SDH} + 0.44 * DR_{MFH}$$

where: DR_{OFH}: damage ratio for one-family homes and poor/average building quality,

DR_{SDH}: damage ratio for (semi-)detached houses and poor/average building quality,

DR_{MFH}: damage ratio for multifamily houses and poor/average building quality.

The resulting loss model is shown in Fig. 2. For the second model stage (FLEMOps+) a scaling factor of 1.58 for heavy contamination and no precaution was used (see Tab. 1). Fig. 2 demonstrates that FLEMOps adapted to Eilenburg is theoretically within the range of the three stage-damage functions mentioned before. However, the advantage is that it takes into account the building characteristics of the area under investigation.

In addition, a dasymetric mapping approach was applied to disaggregate building asset values. Such exposure data are commonly provided at the municipal level; for loss estimations they have to be disaggregated to a finer spatial scale. To get a realistic distribution of the asset values, land cover data are used as ancillary data. By assigning a weight to each land cover class, the total municipal asset value is disaggregated within the municipality under study. In FLEMOps, the mapping technique of Mennis (2003) was adapted.

Figure 2

2.6 Vulnerability model type III: flood loss estimation on the micro-scale

On the micro-scale the model FLEMOps was applied in two variants: First, the mean damage function that was used on the meso-scale (Fig. 2) was applied to single buildings. Affected buildings were determined by means of the official land register. For the flood loss calculation, a mean property value was uniformly assigned to each affected building (Tab. 1).

In the second approach, building-type-specific damage models were used together with a mean property value per building type. The flood loss estimate was corrected considering the share of buildings with high and average quality and the share of different levels of precaution and contamination in the municipality under study. The resulting functions are shown in Fig. 3. For this approach, a distinct building type had to be assigned to each building in the land register. This step is particularly prone to uncertainty since the only information available is a rough classification of the building use: residential use on the one hand and commercial, industrial or other uses on the other hand. Many buildings in Eilenburg were attributed to the second category. However, a lot of these buildings in the town centre are actually used for both residential and commercial purposes and were thus included in the flood loss estimation. Further, no information was available about the building types. Thus, types had to be assigned on the basis of the building area and geometry.

Figure 3

3 Case study

For the comparative study we selected the municipality of Eilenburg in Saxony, Germany. It suffered enormous damage in August 2002, when the Mulde river, a tributary of the Elbe, flooded the whole city with inundation depths up to 5 m in the vicinity of the river and 3 m in the town. An important hydraulic feature is the Mühlgraben, a bypass of the Mulde river (Fig. 4), which is diverted from the main stream approx. 10 km upstream of Eilenburg and conveys water through the western part of the city. It rejoins the Mulde within the municipal boundary of Eilenburg. In August 2002, this caused a flooding of the old city from two sides,

thus aggravating the already worse flooding condition. Fig. 4 shows the topographical map of the city and surroundings.

Figure 4

Because of the enormous extent, the flooding was well documented, as was the flood loss. A shapefile indicating the maximum inundation extent was surveyed from satellite imaging and water marks (Fig. 5). Flood depths were recorded from water marks at 380 buildings in the city centre thus yielding detailed point information of inundation depths in the town and were provided by Schwarz et al. (2005 pers. comm.). These extensive data could be used for the calibration of the inundation models. Upstream boundary conditions were given by the measured hydrograph at the gauge Golzern, which is the closest gauging station. However, the next and last downstream gauging station of the Mulde was destroyed during the flood and consequently the downstream boundary could not be used for model calibration.

Figure 5

The total flood loss is also well documented by the Saxonian Relief Bank (SAB) because a huge flood loss compensation program was released after the flood. The SAB kept track of the repair works and costs as declared by the property owners and their reconstruction aid. According to the flood loss compensation guidelines (SMI 2002), costs for repairing or replacing damaged household contents and/or damaged outside facilities (fences, plants etc.) were excluded from the compensation. Therefore, the eligible repair costs almost represent the total building damage. In Eilenburg, the sum of the eligible costs amounted to 77.12 million Euro consisting of 765 records with a minimum 4198 Euro and a maximum of 2365722 Euro (Tab. 1). This leaves us with a comparatively accurate estimation of the monetary building damage in the town, against which the different risk analysis model combinations could be tested. In Tab. 1 and Fig. 5 also other input data necessary for the flood loss models are summarized. Private precaution was negligible in Eilenburg before the flood in 2002 and additionally

the floodwater was contaminated by oil in more than 50% of the affected households (Tab. 1).

Table 1

4 Results

4.1 Hydraulic model setup

The 1D/2D-model utilises the official 25 m resolution DEM of Germany for the floodplain inundation part. The river bed elevation and slope was extracted from bathymetrically surveyed cross sections of the river in the reach. The model assumes a rectangular channel, which was defined from the surveyed bank widths and bed elevations. The spatial distribution of surface roughness coefficients is based on the CORINE land cover data as at the year 2000. The basic roughness parameters were derived from tabulated values (Chow, 1973) and further modified during the calibration of the model. In the calibration procedure the roughness value assumed for a whole land cover class was modified. However, because of the fixed time stepping used for the simulations, a pronounced insensitivity of the model to floodplain roughnesses could be observed, as already stated in Hunter et al. (2005). Thus, the main calibration parameter was the channel roughness.

The 2D-model operated on a mesh of 46417 nodes and 87945 triangular elements (Fig. 6). Floodplain and river topography were sampled onto the mesh using nearest neighbours from the 25 m DEM, and in addition some channel and bank node elevations are taken from channel surveys and linearly interpolated between 18 cross sections. Channel plan form and the extent of the domain were digitised from 1:25000 maps of the reach. The spatial roughness coefficients distribution was introduced in a similar procedure as in the 1D/2D-model, as well as the calibration.

Figure 6

4.2 Hazard analysis

Figures 7a-d show the results of the benchmark scenario and the hydraulic
models. It can be seen that all models match the inundation extent very good. This
visual impression is also corroborated by the flood area index, defined as the ratio
between the union area of simulated and mapped inundation to the intersection
area of simulated and mapped inundation, of more than 96% of all models (Table
2). However, due to the specific morphology of the flood plain, which is a rather
flat valley confined with steep hillslopes on both sides, this indicator is not very
meaningful. The simulated inundation depth at the valley sides could differ
several meters without changing the inundation extent much and thus the flood
area index. Especially the interpolation method profits from this peculiarity.
Better indexes are the mean absolute error (MAE), the root mean square error
(RMSE) and the bias of the simulation results from the measured maximum
inundation depths at 380 buildings located in the city centre. Figure 8 compares
the simulated and observed water levels in a scatter plot and illustrates the biases
of the models. The 1D/2D and 2D-simulations perform best with a small bias of -
0.05/-0.03 m and a MAE of 0.60/0.64 m respectively (Tab. 2). Thus the
performance of these approaches is comparable to the benchmark scenario, which
has a bias of 0.05 m and a mean absolute error of 0.61 m. They even outperform
the benchmark in respect to RSME, thus indicating a better simulation of the
inundation dynamics as compared to the static benchmark. The bias of 0.28 m of
the interpolation method indicates that this approach systematically overestimates
the inundation depths, especially smaller depths (cf. Fig. 8). Figure 8 also shows
some extreme overestimations of 3-5 m at the same points for all models. At these
points the quality of the DEM has to be questioned, rather than the quality of the
simulation results.
The runtimes of the models differed significantly, as expected from the
complexity levels. The 2D-model required approximately 10 hours to simulate the
5 day flood wave, whereas the 1D/2D-model needed about 20 minutes. Also, the
time needed for the model setup is significantly larger for the full 2D-model,
because it doesn't operate directly on the DEM, but on a mesh required by the
finite element code, which has to be constructed from the DEM first.
Additionally, the imprinting of the real channel geometry in the mesh deduced
from cross section surveys has to be done carefully, which is again more time

consuming than in the case of the 1D/2D-model. And finally the results of the 2D model, giving the inundation depths at the mesh nodes, have to be interpolated to a square grid for a continuous spatial representation of the inundation, i.e. an inundation map. This post-processing step doesn't require much time, but may introduce some uncertainties, because the selection of the interpolation method and the associated parameters may influence the inundation map significantly. For the map shown in Fig. 7 a nearest neighbour interpolation with a search radius of 20 m was used. However, tests with different search radii did not cause significant changes in the performance assessment of the 2D model in this case.

The simulation time of the interpolation model is more or less the time required for the preparation of the input data and the intersection of the flood levels with the DEM. This usually needs a number of verification steps, which can hardly be automated, until a satisfactory result is obtained. Therefore the preparation time has to be estimated in the range of one to several days.

Figure 7

Table 2

Figure 8

4.3 Flood loss estimation

The flood loss estimates on the basis of the three hazard models and the benchmark scenario on the one hand and the various flood loss models on the other hand are summarized in Table 3. The relative errors from the official flood loss information of 77.12 million Euro are given in Table 4, the absolute errors in Table 5.

However, in order to define a more objective rejection criteria, a resampling method (bootstrap) was performed with the 765 damage records in order to derive a confidence interval associated to the total flood loss figure. The data set was resampled 10^4 times yielding a median of 76.89 million Euro, a 2.5-percentile of 72.00 million Euro and a 97.5-percentile of 83.39 million Euro. We further assumed that only model combinations with an estimated loss falling within this

95% confidence interval are accurate enough. With this assumption only five model combinations can be accepted (in order of increasing error):

- the 1D/2D- hydraulic model in combination with the meso-scale flood loss model FLEMOps+ considering water level, building type and quality as well as contamination and precaution (this model combination achieved the best estimate),
- the linear interpolation in combination with the micro-scale flood loss model #1,
- the benchmark scenario in combination with the meso-scale flood loss model FLEMOps+,
- the full 2D-model in combination with the meso-scale flood loss model FLEMOps+, and
- the benchmark scenario with the micro-scale flood loss model 1 (see also Tab. 3).

These model combinations show a relative error of equal or less than ±6%. A relative error of 10%, e.g. as resulting from the combination of the linear interpolation and FLEMOps+ (see Tab. 4), is already assumed to be unacceptable, since the estimate is outside of the 95% confidence interval of the resampled data. Thus, with the proposed rejection criteria only two flood loss models - FLEMOps+ and the micro-scale model #1 - can be accepted. This result is confirmed by further model validations in Saxony presented in Olschewski (2007). Tab. 3 and 4 demonstrate that some flood loss models in combination with the benchmark scenario tend to underestimate the flood loss (ICPR, MURL, FLEMOps), while others (HYDROTEC, Micro #2) tend to overestimate. In general, this performance can also be found when the three other hazard scenarios are used. However, the slight overestimation of the hydraulic situation by the linear interpolation is compensated by an underestimation of the flood loss using the Micro #1 flood loss model. (Tab. 4, Tab. 5). We have to conclude that one gets right results with this combination, but for wrong reasons.

If the mean relative (MRE) and absolute errors (MAE) are calculated per flood loss and per hazard model as done in Tab. 4 and Tab. 5, then the following aspects can be retrieved: From all flood loss models the meso-scale model FLEMOps+ performs best, i.e. it produces the lowest MRE as well as the lowest MAE. The second best model is the micro-scale model #1, the third best the stage-damage

function HYDROTEC. The micro-scale model #1, however, shows a slightly higher standard deviation of the MAE. This may indicate that the model reacts more sensitive to changes in the inundation pattern and depths.

The worst results were obtained with the stage-damage functions MURL and ICPR. These models grossly underestimated the building flood loss in Eilenburg. The low standard deviation for the MURL-model reflects that the model hardly reacts to differing inundation depths as is illustrated in Fig. 2. On the opposite, the micro-scale model #2 tends to overestimate the flood loss. In general, the application of the micro-scale models is hampered by the poor information about the building use and building types in the land register. Therefore, building types were assigned on the basis of the building area and geometry. Probably, too many buildings were classified as multifamily houses by this procedure resulting in high flood loss estimates of micro-scale model #2.

In comparison to the heterogeneous results of the flood loss models the MAEs for the three hazard models are quite similar. The overall performance fits to the performance evaluation shown in Fig. 8 and Tab. 2. However, the standard deviations of the MAEs are much higher than the standard deviations of the MAEs of most flood loss models (Tab. 5). It therefore has to be concluded that the total flood loss estimates are more influenced by the choice of the flood loss model than by the choice of the hydraulic model.

Table 3

Table 4

Table 5

5 Discussion and Conclusions

All hydraulic models were able to simulate the maximum water levels of the August 2002 flood within certain accuracy levels. The 2D and 1D/2D-model gave the best overall performances, with good matches to the surveyed inundation depths and extent, with only little bias. Their overall performance is comparable to the benchmark model. They even yielded better results than the benchmark in respect to RMSE, thus indicating a better mapping of the inundation dynamics, as one had to expect. However, the long runtime of the 2D model was a major

obstacle in the calibration process. Calibration was absolutely necessary, because the results obtained with the roughness parameters assumed from literature did yield satisfying results. This is still the major drawback of 2D hydrodynamic models, even in times of ever increasing computational power.

The interpolation method worked also well in this case, but produced a significant bias by overestimating especially small inundation depths. This is a result of the neglect of hydrodynamic features, which is inherent to the method. Despite the comparatively good results of the method it has to be kept in mind that the method cannot be applied to both mountainous areas and flat lowland regions where hydraulic characteristics and volume control significantly influence flood extent and inundation depths.

However, the variability of the hazard modelling results is small in comparison to the variability of the flood loss estimates as shown in Table 4 and Table 5. It has to be concluded that the selection of the flood loss model has a much larger impact on the final risk estimate than the selection of the hazard model. In this respect the meso-scale flood loss model FLEMOps+ including additional factors (oil contamination, precaution) yielded a remarkable improvement of the flood loss estimation in this case study, as compared to simple stage-damage functions. The micro-scale flood loss models did not yield comparable or even better results than the meso-scale model FLEMOps+ since their application was hampered by rough assumptions about the uses and types of the affected buildings. These results can only be improved by a field survey of the building stock or by help of high resolution optical satellite images.

The study also showed the necessity of evaluating the performance of the hazard and vulnerability models separately from each other. Otherwise apparently reasonable flood loss estimations can be achieved, but for wrong reasons. This means that the error caused by the hazard model could be compensated by errors of the vulnerability model. While this may be regarded as a pragmatic solution for the problem at hand, it will surely cause problems when a temporal as well as spatial transfer of the approach is intended, besides the fact that such a solution is not acceptable from a scientific point of view.

As a summary it can be concluded from this case study, that the 1D/2D-hydraulic model in combination with the meso-scale flood loss model FLEMOps+ is the best compromise between data requirements, simulation effort, and an acceptable

accuracy of the flood loss estimation and would be our recommended approach for a thorough flood risk analysis in the area. The use of water masks intersected with a DEM in combination with FLEMOps+ also proved to be an efficient method for flood loss estimation. This method would be a good choice for quick flood loss estimations shortly after a flood.

However, since this paper presents only a case study, further test cases in other regions should be undertaken to corroborate the general applicability of this conclusion. The need for further tests and validations underlines the necessity of a thorough documentation of future flood events concerning the flood characteristics as well as the flood losses.

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Figure captions

Figure 1: The comparative model matrix. Dark colours represent match in complexity, light colours a mismatch.

Figure 2: Different meso-scale stage-damage functions and the meso-scale damage model FLEMOps adapated to the municipality of Eilenburg.

Figure 3: The meso-scale and micro-scale damage function of the model FLEMOps+ adapted to the municipality of Eilenburg (OFH: one-family home, SDH: (semi-)detached house, MFH: multi-family house).

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Figure 4: Investigation area overview and topographical map of Eilenburg

Figure 5: Unit-specific asset value of residential buildings for the meso-scale damage models type I and II (based on data of Kleist et al. (2006) and dasymetric mapping algorithm adapted from Mennis (2003)) and the extent of the inundation area in August 2002 in Eilenburg (data source: UFZ Halle-Leipzig, 2003, pers. comm.).

Figure 6: Layout of the mesh of the full 2D-finite element model

Figure 7: Results of the hazard models: a) flood mask and DEM, b) linear interpolation, c) 1D/2D-model, d) 2D-model

Figure 8: Scatterplot (Bias) of the surveyed inundation depths vs. simulation results at 380 buildings.

Tables

Table 1: Input data for the damage assessment in the municipality of Eilenburg
(Saxony, Germany) for the flood event in August 2002.

Building characteristics and asset information	
Number of residential buildings according to INFAS Geodaten	3505
Share of buildings with high or exclusive quality according to INFAS Geodaten	7 %
Share of buildings with average or low quality according to INFAS Geodaten	93 %
Total assets of residential buildings in the municipality of Eilenburg (Kleist et al., 2006)	€ 771.31 million
Mean asset value for residential buildings	220060 €
Mean asset value for one-family homes	104324 €
Mean asset value for (semi-)detached houses	92506 €
Mean asset value for multifamily and apartment houses	539562 €
Telephone survey after the flood event in August 2002 (Kreibich et al., 2005; Thieken et al., 2005)	
Number of surveyed households in Eilenburg	37
Share of households not affected by contaminated floodwater	24.3 %
Share of households affected by heavily contaminated floodwater (oil contamination)	64.9 %
Share of households that performed NO precautionary measures	89.1 %
Share of households that performed ONE precautionary measure	5.4 %
Share of households that performed MORE THAN ONE precautionary measure	5.4 %
Information of the Saxonian Relief Bank (Sächsische Aufbaubank - SAB, as at 17 February 2005)	
Total eligible repair costs for damage to residential buildings in August 2002	€ 77.12 million
Number of buildings to be repaired	765

Table 2: Performance of the hazard models in simulating the flood of August 2002

performance / model	surveyed inundation depths			flood extent
	bias [m]	mean absolute error [m]	root mean square error [m]	flood area index [%]
flood mask and DEM	0.05	0.63	1.01	100
linear interpolation	0.30	0.62	0.87	96.43
1D/2D-hydraulics	-0.05	0.60	0.88	96.05
2D-hydraulics	-0.03	0.64	0.82	96.96

Table 3: Estimated damage (given in million Euro) at residential buildings in Eilenburg due to the flood event in August 2002.

Hazard scenario	Damage model						
	ICPR	MURL	HYDRO -TEC	FLEMO ps	FLEMO ps+	Micro #1	Micro #2
flood mask and DEM	34.91	10.37	97.88	50.40	79.63	72.38	103.29
linear interpolation	39.75	11.47	105.88	53.78	84.97	76.59	109.02
1D/2D-model	34.50	9.78	95.03	48.68	76.92	67.50	94.67
2D-model	33.82	10.18	98.97	50.64	80.01	68.77	100.70

Table 4: Relative errors (given in per cent) of the estimates from the reported building repair costs of 77.12 million Euro. MRE: Mean relative error, SD: Standard deviation.

| Hazard scenario | Damage model | | | | | | | MRE | SD |
	ICPR	MURL	HYDRO-TEC	FLEMO ps	FLEMO ps+	Micro #1	Micro #2		
flood mask and DEM	-55%	-87%	27%	-35%	3%	-6%	34%	**-17%**	**44%**
linear interpolation	-48%	-85%	37%	-30%	10%	-1%	41%	**-11%**	**46%**
1D/2D-model	-55%	-87%	23%	-37%	0%	-12%	23%	**-21%**	**41%**
2D-model	-56%	-87%	28%	-34%	4%	-11%	31%	**-18%**	**44%**
MRE	**-54%**	**-86%**	**29%**	**-34%**	**4%**	**-8%**	**32%**		
SD	**4%**	**1%**	**6%**	**3%**	**4%**	**5%**	**8%**		

Table 5: Absolute errors (given in million Euro) of the estimates from the reported building repair costs of 77.12 million Euro. MAE: Mean absolute error, SD: Standard deviation.

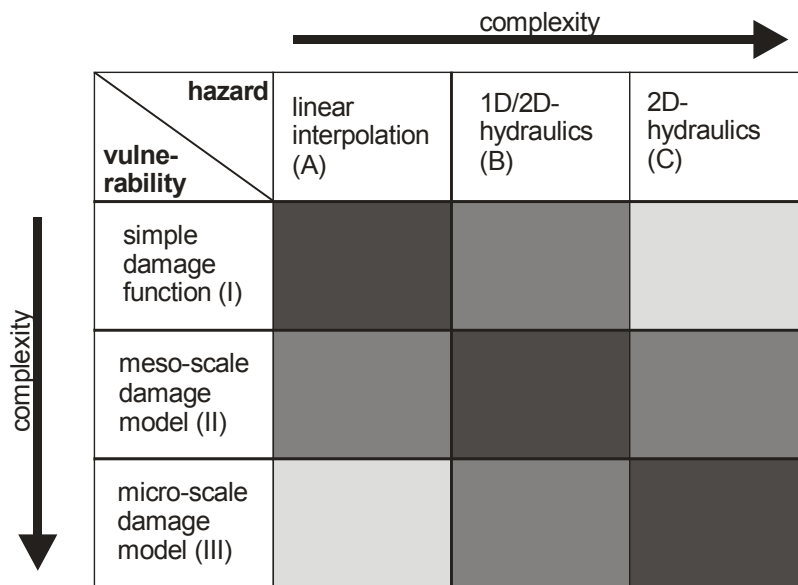| Hazard scenario	Damage model							MAE	SD
	ICPR	MURL	HYDRO-TEC	FLEMO ps	FLEMO ps+	Micro #1	Micro #2		
flood mask and DEM	42.21	66.76	20.75	26.73	2.51	4.74	26.17	**27.12**	**22.16**
linear interpolation	37.37	65.65	28.76	23.35	7.84	0.53	31.90	**27.91**	**21.23**
1D/2D-model	42.62	67.34	17.90	28.44	0.21	9.62	17.55	**26.24**	**22.59**
2D-model	43.31	66.95	21.84	26.48	2.89	8.35	23.57	**27.63**	**21.71**
MAE	**41.38**	**66.68**	**22.31**	**26.25**	**3.36**	**5.81**	**24.80**		
SD	**2.71**	**0.72**	**4.60**	**2.12**	**3.22**	**4.08**	**5.95**		

Figures
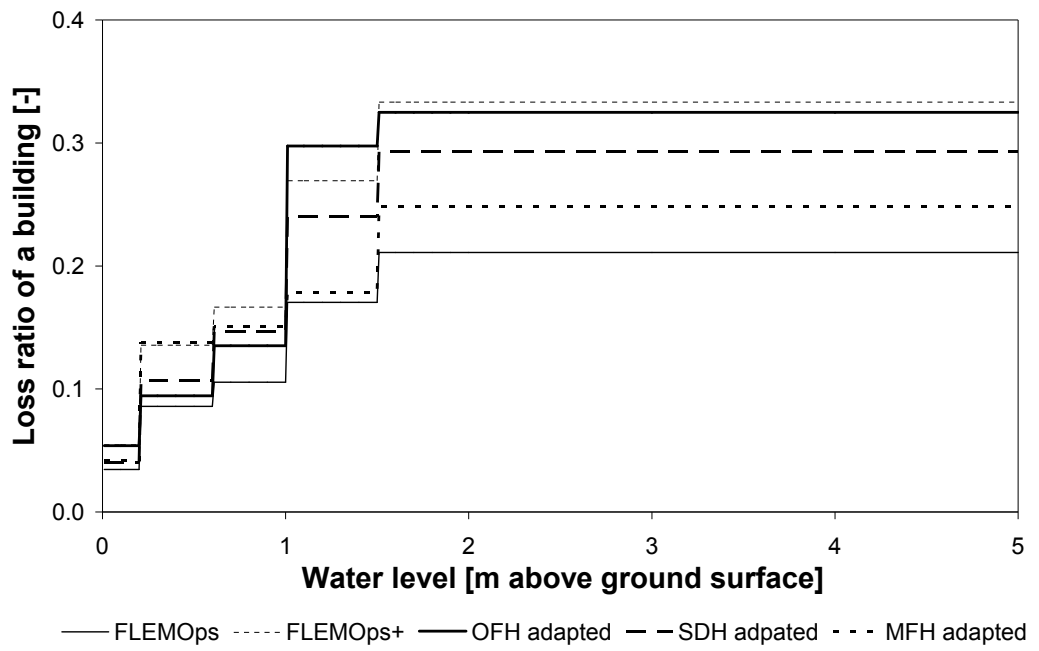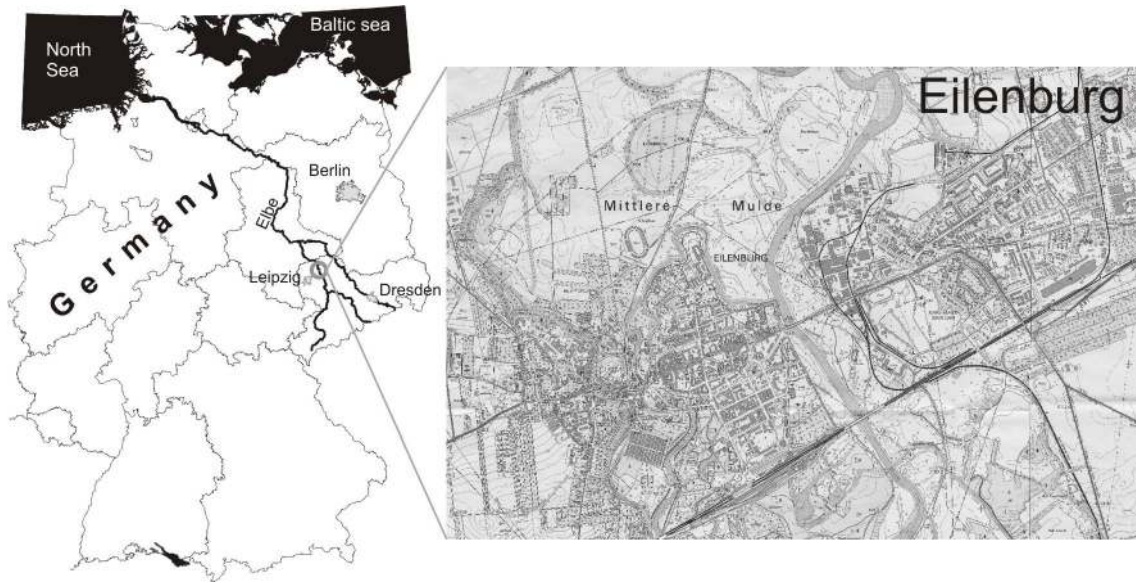
Figure 1

Figure 2
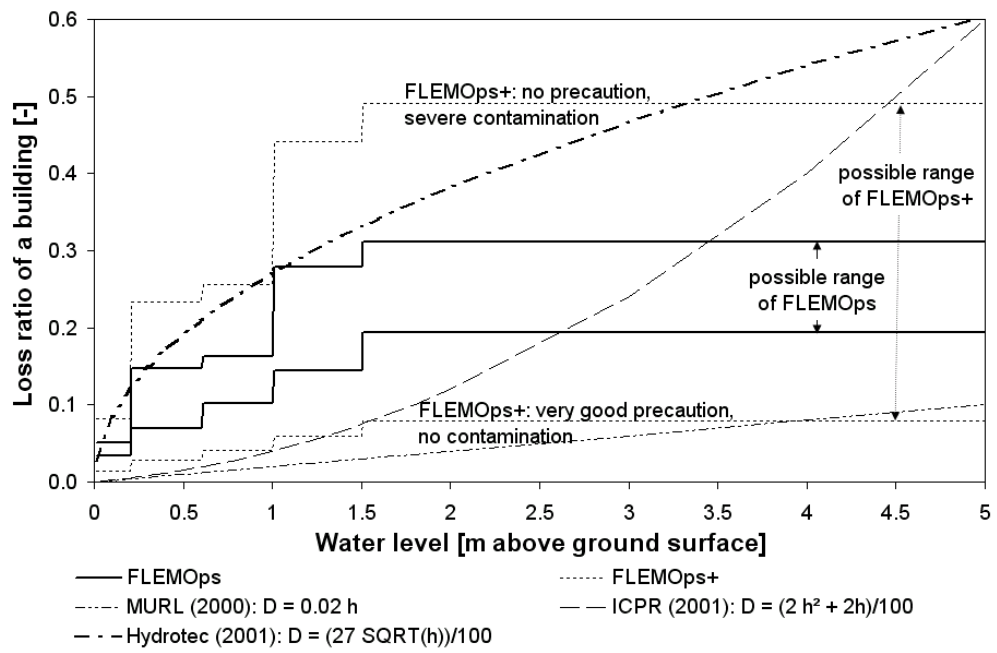
Figure 3

Figure 4

Figure 5

1   0   1 Kilometers

/// Area inundated in August 2002
Unit asset value for residential property [€/km²]
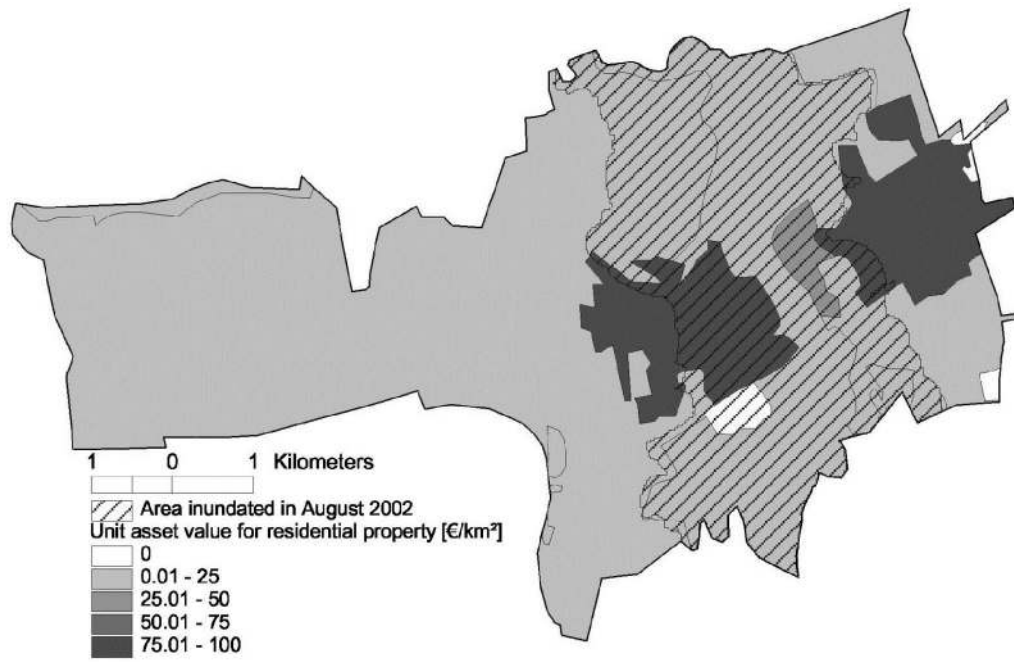   0
        0.01 - 25
        25.01 - 50
        50.01 - 75
        75.01 - 100

Figure 6

Figure 7

Figure 8